How Many Acoustic Waves Can Dance On The Head Of A Sonic Log?

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Introduction

The discussion of acoustic wave theory and practice in the literature is exceedingly complex and confusing. This is partly because it is a complex subject and the sound waves are moving in a complex environment (the borehole, borehole wall, and rock with porosity filled with an unknown fluid mixture). It is also confusing because authors have used different terminology for the same acoustic waves. In some cases, there are at least six names for the same acoustic wave. In addition, there is a confusing mix of terminology taken from the "plane wave" environment at the Earth's surface (earthquake and seismic environments) and the very different cylindrical geometry of the borehole.

Many authors have not clarified the conditions of their experiments (eg. borehole size, tool size and construction material, energy source type and frequency range, velocity detection and calculation method, fluid-rock-borehole velocity contrasts). These factors affect which acoustic modes are transmitted. Conclusions drawn from one experiment will not necessarily apply to another with different assumptions.

The following material is my simplified version. It is intended as a tutorial only - not as a detailed theoretical treatise. The emphasis is on wireline logging, although LWD is mentioned briefly.

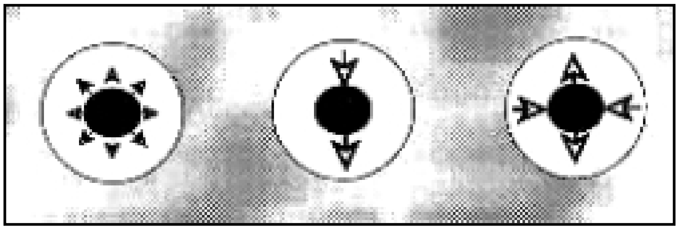

Figure 1: Direction of pressure waves from (left to right) monopole, dipole, and quadrupole sources (from Zemanek et al, 1991)

Energy Sources for Acoustic Logs

Acoustic log source types fall into three categories: monopole, dipole, or quadrupole, illustrated in Figure 1.

1. **Monopole sources** emit sound energy in all directions radially from the tool axis. They are sometimes called axisymmetric or radially symmetric sources. Commercial wireline sonic logging tools, from the earliest tool to the present-day, carry a monopole source along with two or more monopole receivers. This tool arrangement creates the conventional compressional sonic log that we are all familiar with.

   Sound energy from the source that reaches the rock at the critical angle is refracted (bent) so that it travels parallel to the borehole inside the rock. This energy is refracted back into the borehole, and strikes the receivers. The difference in time between arrivals at the receivers is used to estimate the travel time, or slowness, of sound in rock. Sound velocity is the inverse of slowness.

   In fast formations, this tool design can also receive shear waves generated in the formation, where some of the compressional energy is converted to shear energy. A fast formation is a rock in which the shear velocity is faster than the compressional velocity of the fluid in the borehole. A slow formation is a rock in which the shear velocity is equal to or slower than the fluid velocity.

   The monopole source also generates a shear wave on the borehole surface in fast formations, called a pseudo-Rayleigh wave. The converted shear and the pseudo-Rayleigh arrive at the monopole detector with nearly the same velocity and cannot usually be separated. Monopole sources also generate the Stoneley wave in both fast and slow formations. The low frequency component of the Stoneley is called the tube wave. More detailed descriptions of all wave modes are given later in this article.

2. **Dipole sources** and receivers are a newer invention. They emit energy along a single direction instead of radially. These have been called asymmetric or non-axisymmetric sources. They can generate a compressional wave in the formation, not usually detected except in large boreholes or very slow formations. They generate a strong shear wave in both slow and fast formations. This wave is called a flexural or bender wave and travels on the borehole wall (Figure 2).

   Unlike the pseudo-Rayleigh from a monopole source, which also travels on the borehole wall at near shear velocity, the flexural wave field is asymmetric.

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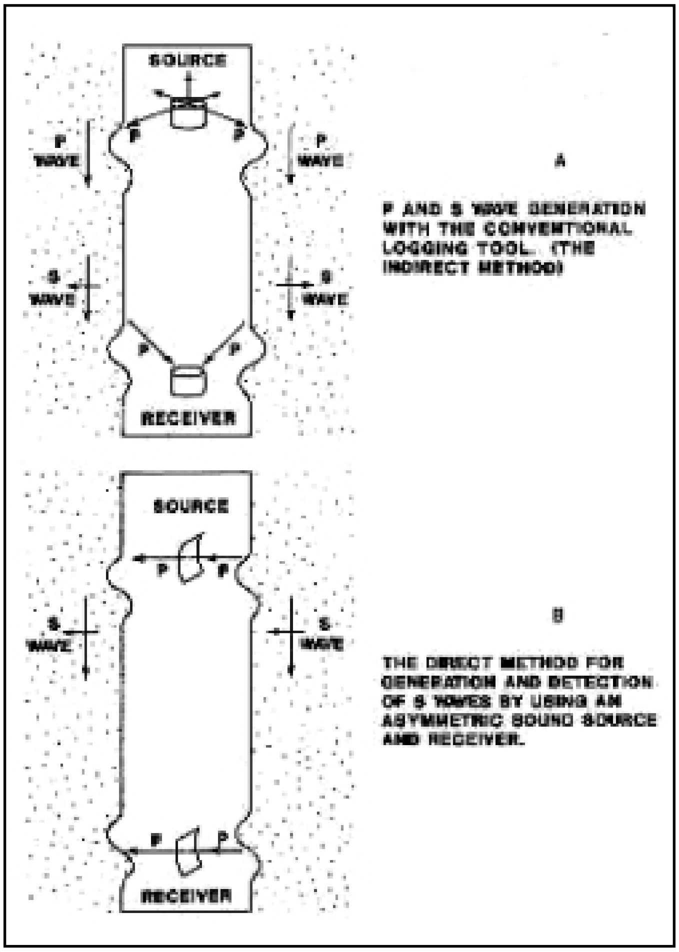

Figure 2: Shear wave propagation from monopole source (upper) and dipole source (lower) (from Zemanek et al, 1991)

Modern open-hole sonic logging tools carry both monopole and dipole sources and receivers so that compressional and shear arrivals can be recorded in slow and fast formations. The sources are fired alternately; the sound from one source will not interfere with the other.

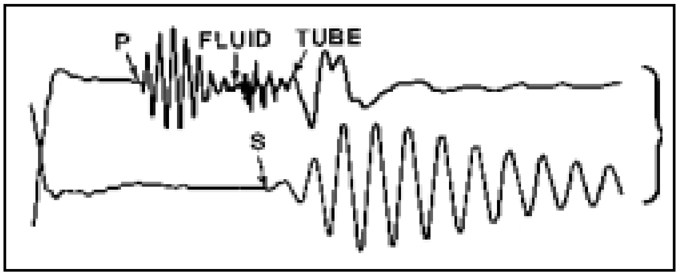

Figure 3: Monopole (upper) and dipole (lower) waveforms in a slow formation (from Zemanek et al, 1991)

Some modern sonic logging tools have two sets of dipole sources set orthogonally, with corresponding dipole receivers. Shear data can be recorded in two directions in the formation. These are called crossed-dipole tools. After suitable processing, the two acoustic velocity measurements are translated into a minimum and maximum velocity.

The ratio of these velocities is a measure of acoustic anisotropy in the formation. This is an important property in formation stress analysis, hydraulic fracture design, fractured reservoir description, and tectonic studies.

Figure 3 (upper) shows a waveform from a monopole source in a slow formation. There is a compressional wave (P) but no shear arrival. The dipole waveform (lower) at the same depth shows no compressional but good shear (S) arrivals. Notice that the shear wave arrives after the fluid wave (the definition of a slow formation).

In a fast formation, the shear arrival will be seen on the monopole waveform (Figure 5) as well as on the dipole waveform.

3. **Quadrupole sources** generate asymmetric pressure waves, called screw waves, which behave similarly to those of dipole sources. They can be used on open-hole tools, although no such tool is commercially available. They are more suited to the logging-while-drilling environment where recent developments have shown some success in measuring shear velocity. The quadrupole source generates quadrupole waves, which travel in the collar and the formation, the two being coupled through the annulus. At low frequencies the formation quadrupole travels at the formation shear speed. The quadrupole LWD tool collar is designed to be thick enough that the collar quadrupole mode is “cut off” (very highly attenuated) below some frequency chosen to be well above the frequency used for quadrupole logging, thus minimizing the interference with the formation quadrupole.

   While there are strong collar arrivals on monopole LWD tools, there have been monopole LWD sonic logs operating successfully for many years, using various mechanical and processing techniques to attenuate the collar arrival. For LWD dipole tools, the collar mode interferes with the formation dipole, forming coupled modes where the formation shear speed is difficult to extract.

Dispersion

The velocity of sound varies with the frequency of the sound wave. This effect is called dispersion. Most waves travel faster

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at low frequency (normal dispersion) but tube waves are slightly reverse dispersive in fast formations and normally dispersive in slow formations.

Compressional waves have very little dispersion. The various wave modes used to measure shear velocity are very dispersive, which may account for errors in shear velocity on older logging tools, when high frequency sources were the norm. Today, tools are designed to work below 5 KHz for shear measurements, instead of 20 to 30 KHz on older tools. Typical theoretical dispersion curves for a particular velocity assumption are shown in Figure 4 to illustrate the problem. For larger boreholes and/or slower formations, the dispersion curves shift to lower frequencies.

Real Logging Tools

Modern sonic logs, often called dipole shear sonic logs, usually carry monopole and dipole sources, and generate the measured values for compressional, shear, and Stoneley slowness in different ways depending on the formation characteristics. Such a tool can give us all three measurements in both slow and fast formations.

Earlier tools, commonly called full-wave, array, or long spaced sonic logs, could give us all three measurements in fast formations but shear was not possible in slow formations. Shear could be estimated by a transform of compressional or Stoneley slowness, and this is still done today in many real situations where the dipole log is unavailable. Waveforms were recorded in digital form but were seldom preserved, so reprocessing is not usually possible.

Earlier still, conventional and borehole compensated sonic logs could provide compressional slowness values directly. Shear slowness in fast formations was derived by digitizing an interpretation of the waveform traces or a VDL display of the traces. Most of these tools were short spaced, so it was difficult to pick the shear as the tail of the compressional wave stretched into the shear region. Waveform traces or VDL displays were on film and difficult to process accurately.

Acoustic Transmission Modes

The monopole source generates several wave modes, some of which have been used more or less successfully, to estimate shear velocity. Other wave modes are mentioned in the literature and described here to help clarify terminology. The following comments deal primarily with the monopole wireline tool, but dipole and LWD are mentioned briefly to contrast important differences.

Monopole sources can develop both body and surface waves; dipole and quadrupole sources create only surface waves. Body waves travel in the body of the rock. Surface waves travel on the borehole wall or bounce from the wall to the tool and back to the wall. The surface waves are also called guided waves or boundary waves.

1. **Fast compressional waves,** also called dilational, longitudinal, pressure, primary, or P-waves, are recorded by all monopole sonic logs, beginning in the mid to late 1950's. They are the fastest acoustic waves and arrive first on the sonic wave-

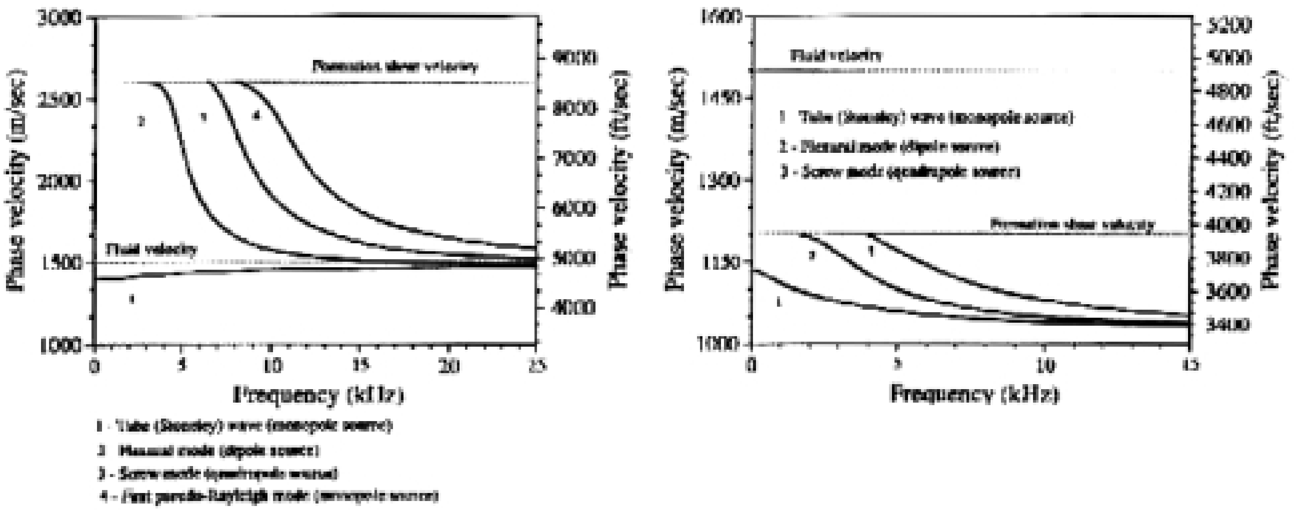

Figure 4: Shear velocity dispersion curves for fast (left) and slow (right) formations (from Zemanek et al, 1991)

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train. Biot called these dilational waves of the first kind and are body wave. The velocity of this wave is related to the elastic properties of the formation rock and fluid in the pores. It has been used successfully for years as a porosity indicator.

The compressional wave is initiated by a monopole energy source and is transmitted through the drilling mud in all directions. Sound traveling at the critical angle will be refracted into the formation, which in turn radiates sound energy back into the mud, again by refraction. The sound waves refracted back into the borehole are called head waves. The compressional head wave is detected by acoustic receivers on the logging tool.

A dipole source generates a noticeable compressional wave in slow formations and in large boreholes, especially on tools running at higher frequencies. The wave is probably present in faster formations and smaller boreholes, but is below the detection level of most processing techniques (see Figure 3).

The velocity of the compressional wave does not vary much with the frequency of the wave. The frequency spectrum of the wave depends on the source frequency spectrum and is usually in the 10 to 30 KHz range.

An acoustic ray path is a line that traces the path that the sound takes to get from the source to the receiver. Compressional waves vibrate parallel to their ray path.

2. **Slow compressional waves** are transmitted, as well as the fast waves described above. It is called a dilational wave of the second kind by Biot. It is also a body wave and travels in the fluid in the pores at a velocity less than that of the fast compressional wave in the formation fluid. Its amplitude decays rapidly with distance, turning into heat before it can be detected by a typical sonic log. No pores, no fluid, no slow compressional wave. Although predicted by Biot in 1952, it was not detected in the lab until 1982 by Johnson and Plona. I am not aware of any practical use for this velocity in the petroleum industry.

   The slow and fast compressional waves as described above should not be confused with the slow and fast velocities found by crossed-dipole sonic logs in anisotropically stressed formations.

3. **Surface compressional waves,** also called leaky compressional, compressional "normal mode", or PL waves, follow the fast compressional wave. This is a surface wave from a monopole source and travels on the borehole wall. Amplitude varies with Poisson's Ratio of the rock/fluid mixture. It is present in both fast and slow formations.

   The wave is dispersive, that is, low frequencies travel faster than high frequencies. It has velocities that range between the fast compressional wave through the formation (Vp) and the fluid wave in the borehole (Vf). The first arrival coincides with Vp and the balance of the wave shows up as a "ringing" tail on the compressional segment of the wavetrain. It usually decays to near zero amplitude before the shear body wave arrives. This monopole leaky compressional wave is strongest in very slow formations, large boreholes, and boreholes with significant near-borehole mechanical damage.

   The number of normal modes depends on source frequency; if frequency is too low, there will be no surface compressional wave. The first normal mode is sometimes called the least normal mode.

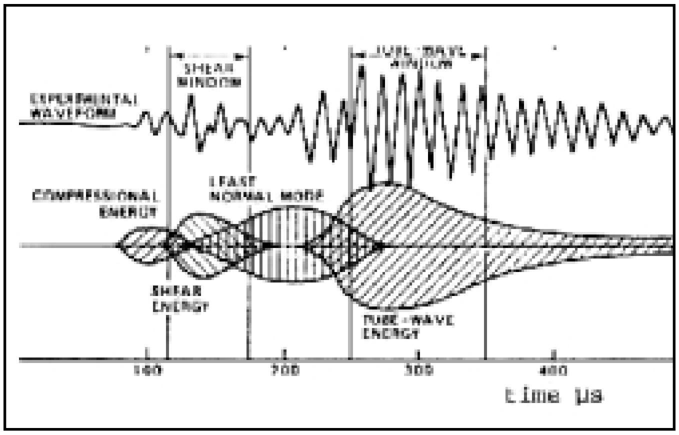

Figure 5: Waveform from a monopole source in a fast formation, showing some of the definitions used in the literature (FROM Paillet, 1991)

4. **Shear body waves,** also called transverse, rotational, distortional, secondary, or S-waves, are generated by conversion of the compressional fluid wave when it refracts into the rock from the wellbore. It converts back to a P wave when it refracts through the borehole to reach the sonic log detector. This wave is also a body wave. The refracted wave returning to the logging tool is called the shear head wave. Shear waves vibrate at right angles to the ray path.

   Monopole sonic logs cannot detect a body shear wave in a slow formation ($V_s < V_f$) because refraction cannot occur. The modern dipole sonic log can generate a shear wave in all formations, but the shear wave is actually a surface wave

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called a flexural wave. A quadrupole source generates what is known as a screw wave with the same result.

When shear is missing on a conventional monopole log (and there is no dipole shear data), it can be estimated by a transform of the Stoneley wave velocity. However, the empirical formula ignores many of the minor variables, so the method is not very accurate.

Shear waves travel at a slower rate than compressional waves. Compressional velocity is approximately 1.6 to 1.9 times higher than shear velocity in consolidated rocks but the ratio can rise to 4 or 5 in unconsolidated sediments.

Shear velocity at sonic log frequencies is not very dispersive but the wave modes used to measure shear velocity are highly dispersive. Low frequency components are faster than high frequency components (see Figure 4). Because even low frequency logging tool sources have a moderate frequency spectrum, the shear body wave will show the "ringing tail" effect on the shear arrival.

Dispersion is important to us for another reason. Lab measured sonic velocities are made at high frequency, usually 1 MHz, and logs make their measurements at low frequency, 3 to 30 KHz, so comparisons of the results from lab and log measurements is difficult.

The shear wave velocity from a sonic log can be used to predict porosity just like the compressional wave. This is not true for 1 MHz lab measurements because the wavelength is too small to treat the rock/porosity mixture as a single coupled material.

Shear velocity is relatively independent of fluid type, so there is no appreciable gas effect on the measurement, unlike the compressional wave, which has a large gas effect. Combined with compressional wave velocity and density data, all the elastic properties of the rock can be computed. Similarly, at seismic frequencies, the shear wave is not significantly affected by the fluid type in a rock so, like the shear sonic log, there is no gas effect on the shear seismic section. Thus, a gas related bright spot (direct hydrocarbon indicator or DHI) on a compressional wave seismic section will have no comparable shear wave anomaly. In contrast, a lithology related anomaly will have a corresponding shear wave anomaly. Thus, it is possible to use shear wave seismic data to evaluate the validity of direct hydrocarbon indicators.

5. **Shear surface waves,** also called pseudo-Rayleigh, multiple-reflected conical, reflected conical, or shear "normal mode" waves, follow the shear body wave. They are a surface wave generated by a monopole source. They are also classified as a guided-wave. Monopole sonic logs cannot generate a surface shear wave in slow formations for the same reason that they cannot generate a body shear wave. Dipole sonic logs can generate a different form of shear surface wave, the flexural wave, but cannot create the shear body wave.

   These waves have also been called slow shear waves and shear waves of the second kind in a few papers. This usage should not be confused with the slow and fast shear velocity found by crossed-dipole sonic logs in anisotropically stressed formations.

   These are called pseudo-Rayleigh waves because the particle motion is similar to a Rayleigh wave on the Earth's surface, but it is confined to the borehole surface. It may also be called a tube wave as it travels on the tubular surface formed by the borehole wall. This latter terminology can be confusing because Stoneley and Lamb waves are also called tube waves.

   Surface waves on the Earth include Rayleigh and Love waves. Particles in Rayleigh waves vibrate vertically in elliptical retrograde motion and cause severe damage during earthquakes. They are also the principal component of ground roll in seismic exploration. Love waves vibrate horizontally, similar to a shear wave, and can be considered as a surface shear wave when found on the Earth's surface.

   The number of normal modes depends on source frequency; if frequency is too low, there will be no pseudo-Rayleigh wave. The first normal mode is sometimes called the least normal (shear) mode.

   This wave is dispersive, that is, low frequencies travel faster than high frequencies. The lowest frequency component arrives at shear velocity (Vs) and reinforces the shear head wave arrival, if one exists. The balance of the energy is dispersed over the interval between shear wave velocity (Vs) and fluid velocity (Vf).

   The Airy phase of the shear normal mode (pseudo-Rayleigh) occurs just after the fluid wave. It can distort the surface shear wave and make it difficult to determine shear velocity. It can also distort the fluid wave and the Stoneley wave arrivals. I am not aware of any practical use for this part of the waveform in the petroleum industry, but it is mentioned often enough in the literature to warrant this brief description.

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In the absence of a shear head wave, which may occur due to attenuation, the onset of the pseudo-Rayleigh wave is used to estimate shear velocity (Vs). If the onset of the pseudo-Rayleigh is low amplitude, Vs may be chosen a little further along the waveform, resulting in a slower value than the correct Vs. When both surface and body shear waves are transmitted, the surface wave may overwhelm the body wave, resulting again in a slow Vs determination. This problem was common in the early days of hand digitized full wave sonic logs, before the advent of computerized shear picking.

If the source does not transmit low enough frequencies, the fastest surface shear wave will be slower than the corresponding body shear wave. If the log processing system picks the surface wave instead of the body wave, it will give a slow Vs. Service companies make an empirical correction for this on flexural dipole logs, but not on monopole shear logs, before presenting the log to a customer.

The Slowness-Time Coherence or STC velocity analysis method, a form of cross-correlation for picking velocity or travel time from sonic waveforms, minimizes this problem. The newest sonic logs use a dispersion corrected STC process. On older logs without the low frequency source, Vs is probably too slow even when STC is used.

If the rock is altered near the borehole wall due to drilling or chemically induced damage, the surface shear wave will be slower than the body shear, which travels in the undamaged formation. A recent paper shows clearly that two shear arrivals can be seen on waveforms from a dipole sonic in young unconsolidated sediment - one through the altered zone, one through the undisturbed formation.

There are lots of reasons why a log might give too slow a Vs. This problem has been the bane of fracture design and mechanical properties calculations for years. As the shear velocity technology gets better each year, we may be able to generate more reliable results.

6. **Stoneley waves** are guided waves generated by a monopole source that arrive just after the shear wave or the fluid compressional wave, whichever is slower. The wave guide is the annulus between the logging tool and the borehole wall. They are also called tube waves or Stoneley tube waves, in some of the literature.

   Various authors have shown the Stoneley wave in slow formations to be slightly dispersive (low frequency arrive faster than the high frequencies); in fast formations it is slightly reverse dispersive (high frequency arrives first).

   Amplitude of the Stoneley wave depends on the permeability of the rock, among many other things. The wave motion acts as a pump forcing fluid into pores and fractures. Higher permeability absorbs more energy, thus reducing amplitude. There is no simple equation for calculating permeability from Stoneley amplitude.

7. **Tube waves,** also called Lamb waves or "water hammer", are the low frequency component of the Stoneley wave (in theory, the zero frequency component).

8. **Fluid compressional wave** or mud wave is the compressional body wave from a monopole source that travels through the mud in the borehole directly to the sonic log receivers. It travels at a constant velocity with relatively high energy. When it occurs after the shear arrival (Vs > Vf), shear detection is relatively easy with modern digital sonic logs.

9. **Direct tool arrival** is sound that travels along the logging tool body. The wireline tool housing is slotted to make the travel path, and hence the arrival time, too long to interfere with other arrivals.

   In the LWD environment, the tool body cannot be slotted like an open hole tool. However, internal and external grooves, or holes filled with acoustically absorbent materials, are used to attenuate the tool body signal. This mechanical filter is designed specifically for the frequency content of the source. Separating the tool direct arrival is still difficult with monopole and dipole LWD sources. The LWD tool direct arrival is negligible at low frequencies for the quadrupole source when the collar wall is thick enough.

Conclusions

If you weren't confused before, you should be by now! Which modes are detected by the sonic log on your desk? Which source was used to generate them? Will the real shear travel time please stand up!

Calculating porosity from shear or compressional data, deriving mechanical properties for fracture design, calibrating shear and compressional seismic data to ground truth, and modeling AVO require a log that measures the real shear travel time. We

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only get approximations in slow formations and maybe not much better in fast formations. Comparison of lab results to log data is meaningless due to frequency effects. Empirical corrections allow us to get by, but is this as good as the world can be?

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2. Qualitative and Quantitative Interpretation of Permeability Using Acoustic Full-Waveform Logs, F. L. Paillet, The Log Analyst, May 1991.
3. Acoustic Waveform Logging - Advances in Theory and Applications, F. L. Paillet et al, The Log Analyst, May 1992.
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These papers have long lists of further reading.

Ross is a Professional Engineer and member of the CWLS, with over 35 years of experience in reservoir description, petrophysical analysis, and management. Many thanks to Ross for allowing us to publish this article.

The Canadian Well Logging Society announces yearly awards for undergraduate and graduate students in engineering and earth sciences. The purpose of these awards is to raise interest and awareness of careers in Petrophysics and Formation Evaluation. Formation evaluation and Petrophysics are the studies of rocks and their fluids as they pertain to the oil and gas industry.

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